AUTOMATED CORE SAMPLE HANDLING FOR FUTURE MARS DRILL MISSIONS

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ABSTRACT

Signs of microbial life on Mars, if they exist, will probably exist underground. This paper describes a robotics system for handling and sub-sampling cores taken from a robotic drill. The system prepares samples for analysis and life detection experiments. This system has been integrated with a drill and other instruments and tested in the field. This paper presents a description of the system and observations from the field test.

Key words: sample handling, Mars drill.

1. INTRODUCTION

The MARTE project (Mars Astrobiology Research and Technology Experiment) is part of NASA's ASTEP astrobiology technology development program. This project explores the science, instrumentation and automation issues in performing a deep (10s of meters) drill operation on Mars, using Rio Tinto Spain as an analog drill site [1, 8, 9]. There are five major pieces to the MARTE system: 1) The Drill Core Service Module (DCSM) being built by NASA Ames serves as the mechanical integration platform for all other subsystems; 2) the Drill system being built by Honeybee Robotics will perform the actual drilling and will remove a 27 mm diameter, 25 cm long core every quarter meter that it drills; 3) the Bore-Hole-Inspection System or BHIS (built by CAB [2] in Madrid) will be lowered periodically into the hole to examine the walls geological possible biological inspection; 4) the various science instrumentation that will inspect the cores and selected sub-samples taken from the cores; and 5) the Core Sample Handling System (CSHS), which is the subject of this paper.

2. THE MARTE CSHS

The Core Storage and Handling System (Figure 1) consists of several robotic devices. The CSHS receives a core from the drill system into the Core Clamp which is a 24 DoF gripper designed to hold tightly onto a core which can be anything from a 27 mm diameter 25 cm rod of solid rock to a pile of chips and gravel. Depending on the consistency of the core, it may be run under a Facing Saw; whose feed rate is autonomously adjusted by the required cutting force for the material at hand. The faced sample is then run under a set of remote science instruments. Finally the core is placed into a random access storage system capable of storing 2.25 m of core (or almost three days of drilling). This storage provides the science team with time to analyze data and decide which if any cores should be subjected to sub-sampling for more detailed biological analysis.

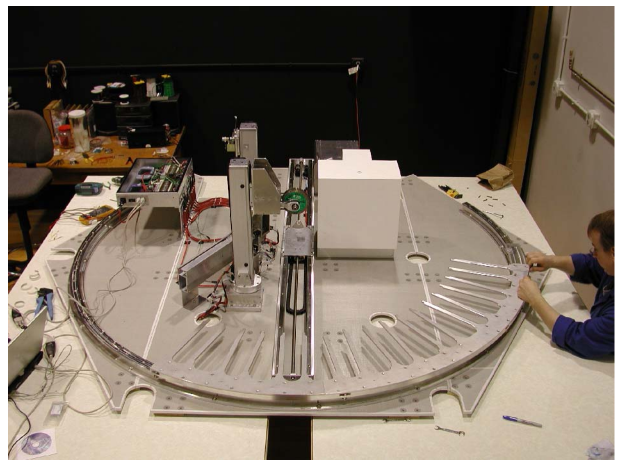

Figure 1. The elements of the CSHS before being integrated to the rest of the MARTE system

If sub-sampling is desired then the effected core is brought out of storage, and an 18 mm segment of the core surrounding the spot of science interest is removed by the Sub-sampling Saw. This sub-piece of the core is then crushed to powder, sifted, and inserted into the SOLID (see [2]) life detection instrument.

The remainder of this paper will describe the pieces of the CSHS and the results from our preliminary field test at Bonny Doons Quarry in Santa Cruz California.

2.1. Core Clamps

The CSHS is equipped with nine Core Clamps (see Figure 2). The Core Clamps serve as fixtures for the retrieved subsurface core samples. The Core Clamps hold the core samples during the sample preparation and maintain a defined position while the different scientific instruments examine and analyze samples.

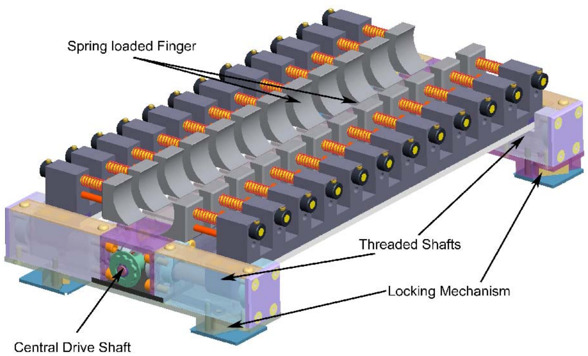

Figure 2. CAD Model of a Core Clamp

The core sample is transferred and placed into the Core Clamp by the Core Sample Hand Off Mechanism. A motor mounted to the Linear Rail Cart closes and opens the Core Clamp. The Core Clamp is symmetric to the longitudinal axis. Each side consists of a bar which holds 12 fingers. The ends of the bar are supported by threaded shafts. The four threaded shafts are simultaneously driven by a central drive shaft via bevel gears. The clamping force is applied to the sample with the concave shaped fingers. The individual spring loaded fingers comply with irregular shaped and fractured samples. This assures a good grip on the core even if it is fragmented into several pieces. In addition, the spaces between the fingers enable the Sub-sampling System to cut through and remove a disc shaped sub-sample (see Figures 10 and 11).

The bottom side of the Core Clamp incorporates a locking mechanism. The locking mechanism provides a rigid connection while the Core Clamp is on the Linear Rail Cart.

2.2. Linear Rail and Cart

The rail mechanism is responsible for positioning the core at each station along its 2 m length where sample preparation or remote science can be done. The rail must feed the samples into the Facing Saw slow enough to allow the top of the rock to be removed without stalling or damaging the saw. The scanning speed under the spectrometer is also critical to obtaining good data. These speeds are on the order of .01 to .1 mm/s. A twin motor design is used to accomplish these low speeds (see Figure 3) as well as a much higher speed to decrease the time spent moving between stations. The higher speed can move the core form one end to the other in approximately 5 minutes. This is needed to keep core processing in sequence with the drill.

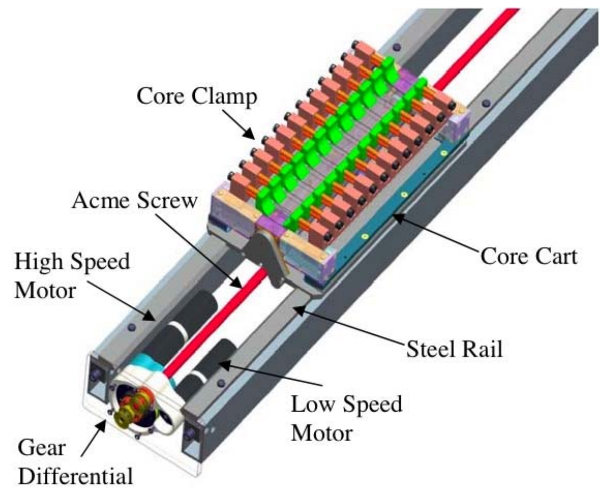

Figure 3. CAD Model Rail Drive

The cart rides along a pair of steel tracks mounted on aluminum tubes to keep them from flexing, these tubes are then mounted to the A' deck[1] 82mm apart. An Acme screw transfers rotational motion from the drive mechanism into linear motion to position the cart. A planetary differential gear assembly is used to turn the screw. The two inputs of the gear train can be combined to produce an output not obtainable with any single input. To reduce computation overhead one input is connected to a high speed motor and the other is used for low speed. The high speed motor is stopped to hold the outer ring of the planetary assembly stationary while the low speed motor is powering the Acme screw and vice versa. This two speed motor assembly keeps all gears in mesh so position calculations between the two motors are never lost.

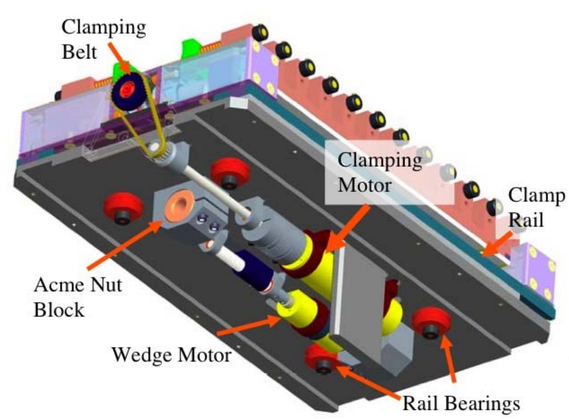

Figure 4. The drive to open and close the clamps is located underneath the cart.

[1] The A' deck is the main equipment deck and is vibrationally isolated from the main structural deck (the A deck) to which the drill is rigidly mounted.

Each Core Clamp is moved between stations on the CSHS by the cart actuated from the Linear Rail. The under side of the cart includes a mechanism to open and close the clamp, to release the clamp from the Storage Comb, Linear Rail bearings, and Acme nut blocks. An *HD systems* dc motor and 80:1 harmonic drive speed reducer drives the clamping belt (Figure 4). The large pulley on this belt mechanism has a grooved socket to allow the spring loaded shaft on each clamp to mate with it (see Figure 4). This way the coupling does not have to be aligned prior to mating the clamp to the cart and torque can be applied to each clamp after it has been put onto the cart.

The two sides of the cart have elevated rails that guide the cart into position when being loaded from the Storage Comb; they hold the cart in place during sub-sampling and facing operations. The wedge motor (see Figure 5) is used to release the clamp from the cart while it is being stored. A small wedge is moved back by another miniature screw mechanism on the under side of the cart. This wedge pushes a lever on the bottom of the clamp upward to disengage the locking mechanism.

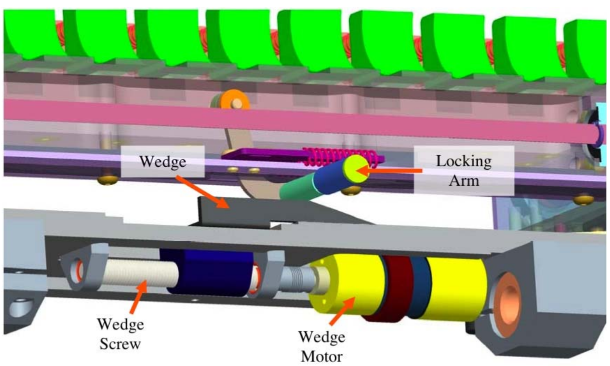

Figure 5. The wedge pushes a lever on the bottom of the clamp to unlock the clamp from the cart.

2.3. Core Storage System

The Core Storage System provides the capability to hold on to interesting core samples and retrieve them to do further analysis. In addition, the Core Storage System is used to dispose of core samples after scientific investigations are completed. The Core Storage System consists of two main components: The stationary Circular Rail and the rotating Storage Comb. The circular shape was employed to most effectively fit on to the hexagonal lander mock up. The rail section expands about two thirds of a full circle and is mounted to the main equipment deck. The structural design is selected in order to maximize the stiffness and minimize the deflection due to flexural deformation in the main equipment deck. The middle of the Circular Rail provides a mounting interface for the Comb Rotation Assembly. Furthermore, the Linear Rail is also mounted to the base plate of the Comb Rotation Assembly. This arrangement ensures proper alignment between the Core Storage System and the Linear Rail.

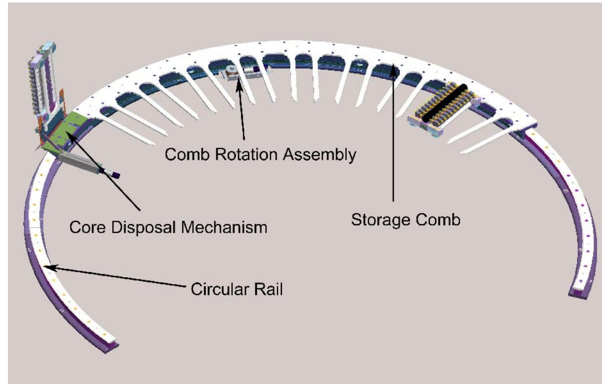

Figure 6. The Storage Comb can store 9 cores and dispose of extra ones.

The Storage Comb consists of nine rigid mounted forks and one fork pivoted at the comb frame (Figure 6). The comb rotation is done by a flexible rack and pinion drive and the position is determined by switch and notch combination. The Storage Comb holds a maximum of nine Core Clamps during nominal operation. In order to perform clamp swap and core disposal operations one clamp storage spot has to be unused. A Core Clamp exchange is performed by unlocking the Core Clamp from the Linear Rail Cart and simultaneously locking it to the Core Storage System. The Linear Rail Cart is pulled out underneath while the Core Clamp rests on the Core Storage System (see Figure 7).

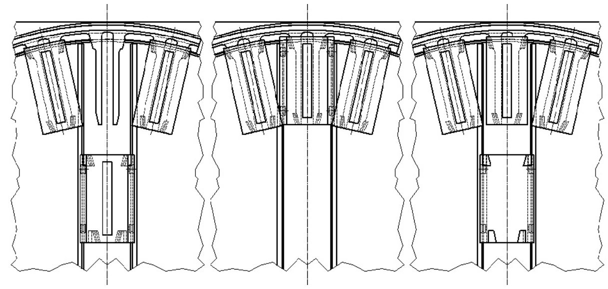

Figure 7. The sequence for moving a clamp onto the storage rail.

The sequence to dispose a no longer needed core sample starts with moving the opened Core Clamp to the Core Disposal Mechanism on the counterclockwise end of the Storage Comb. A powerscrew linkage mechanism rotates the pivoted storage fork to the lander outside where the core sample slides of the Core Clamp and falls to the ground.

2.4. Facing Saw

The Facing Saw removes the external surface of the core sample along its length (Figure 8). This is done to achieve a clean planar surface that will be a standard height for all imaging and spectrometer readings. A dry cutting diamond encrusted masonry blade with a discontinuous circumference to allow better chip removal is lowered into position approximately 5mm from the top of the Core Clamp. The blade is 150mm in diameter and 2.6mm thick. It is powered by a 12V DC motor with a 2.5:1 bevel gear reduction which can be retracted out of the path of the cart in the event that an unconsolidated core is recovered. In this case the core cannot be safely faced so the saw is lifted out of the way.

The retraction mechanism is designed into the main body of the saw. The retraction motor drives a 100:1 worm gear connected to a pinion shaft. The pinion rides on a curved gear rack producing the rotating motion about the retract pivot point (Figure 9).

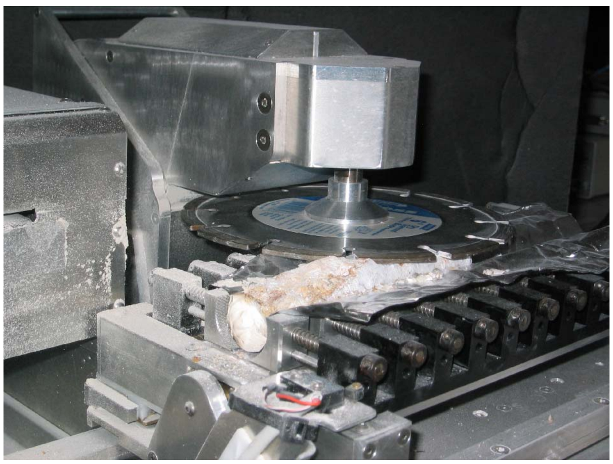

Figure 8. The Facing Saw shaving the top off of a core

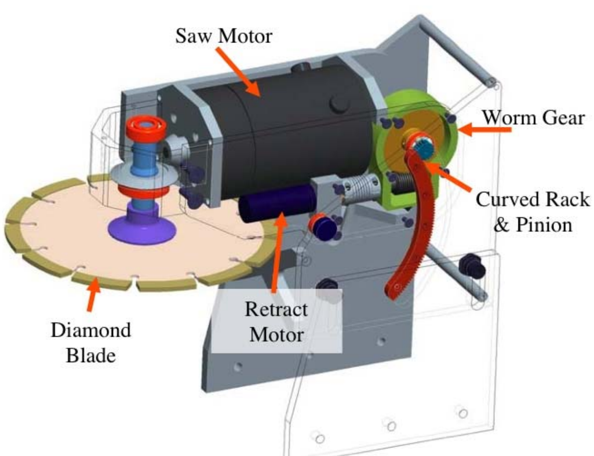

Figure 9. CAD Model of the Facing Saw

2.5. Sub-sampling System

Each rock sample taken by the drill is scanned by the remote instruments then placed on the Storage Comb. If the data shows that a particular segment of the core is of special interest then a sub-sample of that area can be taken.

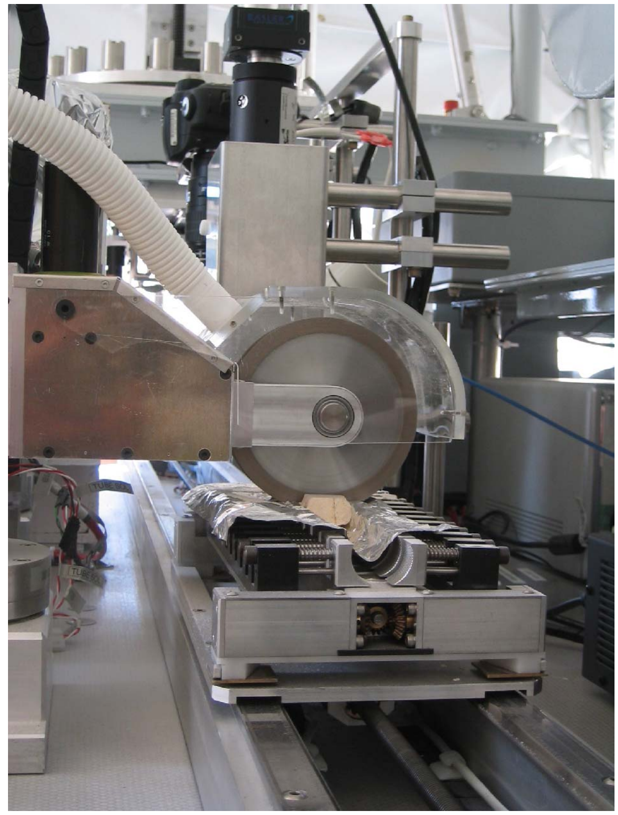

Figure 10. The Sub-sampler cuts through a core

The sub-sampling system uses twin saw blades parallel to each other to cut perpendicular to the axis of the core sample (Figure 10). Once through the sample the blades stop then squeeze together to pick up the rock left between them (Figure 11). Both 100mm diameter blades are driven from the same motor. The blade motor drives a shaft with extra wide pulleys on both ends to allow the belt to move laterally when the arms squeeze together. The arms are supported by two smooth shafts that keep them parallel while a turnbuckle screw provides the squeezing motion (Figure 12). The blades can be opened 39mm and close on a sample as narrow as 14mm wide (the width of a clamp finger). The standard size of a sample is approximately 17mm; that is 20mm spacing between blade centers and about 3mm lost to cuttings. The vertical motion of the saw is accomplished by a ball-screw mechanism encased in an aluminum frame to keep out debris.

2.6. Crushing and Sample Transfer

Once a segment from the core has been extracted by the sub-sample saw, it must be prepared for insertion into the SOLID instrument. SOLID requires 0.75 ml of powder of a grain size of 500μm or smaller. To reduce the core material to this particle size we use a minature rock crusher

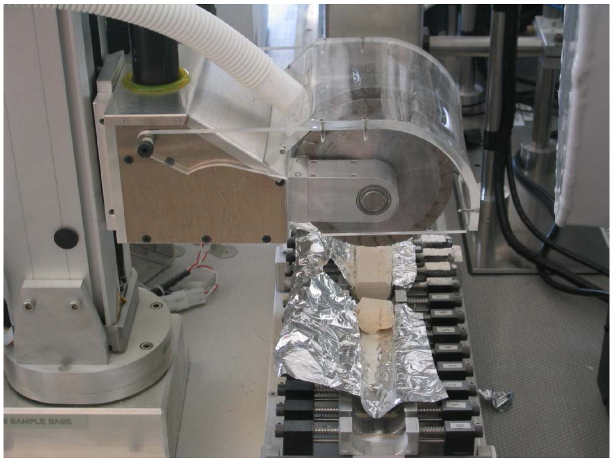

Figure 11. The two blades of the Sub-sampler squeeze together to lift out an 18mm segment of the core

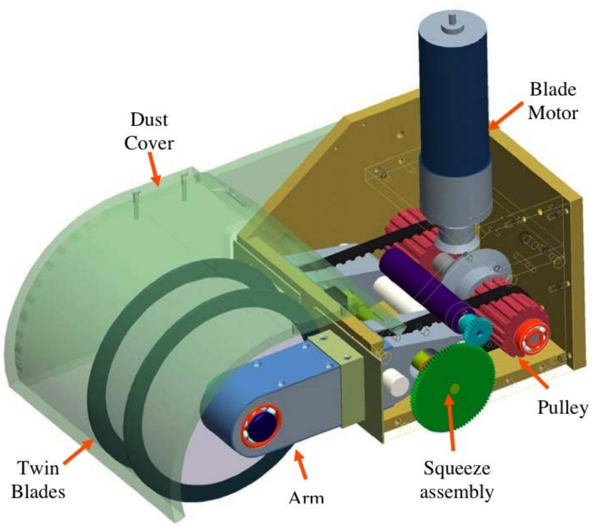

Figure 12. The inner workings of the Sub-sampler saw

developed at JPL [4]. This crusher produces particles of which only about 40% are the correct size – the remainder being too large [3].

To eliminate the oversized particles the CSHS employs a simple sieve (Figure 13). A small vibrator motor is used to help sift the particles through the sieve and onto a chute.

The chute leads down to a core transfer tube. This tube (Figure 14) has a small funnel and some fill holes. The chute touches the funnel causing it to vibrate as well and the small rock particles stream into the funnel, through the holes and into the tube. The tube has a plug on the bottom which can be opened by pressing on the spring-loaded stem at the tube's top. A spring-loaded rack holds 13 tubes in place. When a tube is removed, a solenoid can be fired which moves a release allowing the next tube to slide into place under the crusher.

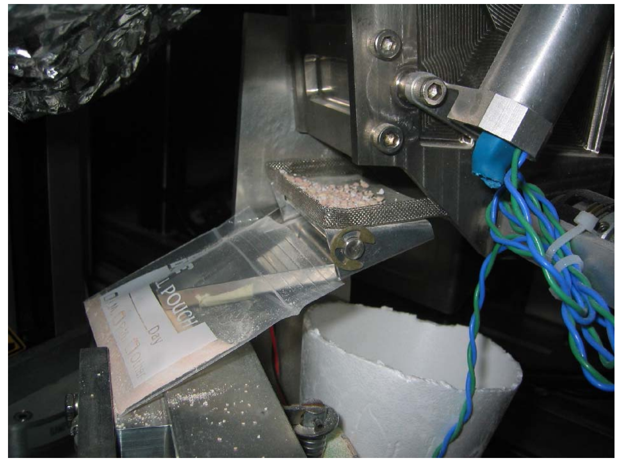

Figure 13. The crusher drops rock fragments onto the sieve which allows particles ≤ 0.4mm to pass through (in this case into a sterile collection bag), and dumps larger fragments into the waste cup.

The sub-sample Transfer Arm is used to move the Sample Tubes full of crushed rock from the tube array and insert it into SOLID. The arm is mounted on an identical rotational/vertical actuation base as the Sub-sampler (Figure 15). It uses a solenoid actuated fist that slides opens once it moves into position to pick up a full tube. The solenoid is released and the fist is held closed by a return spring. The tube can then be lifted and rotated over the SOLID instrument. When it is positioned correctly the lower half of the Sample Tube is lowered into a split gasket sealed opening on top of SOLID. The hammer motor is turned on to release the contents of the tube. The motor spins a crank that is connected to a hammer which depresses the spring loaded seal on the bottom of the tube.

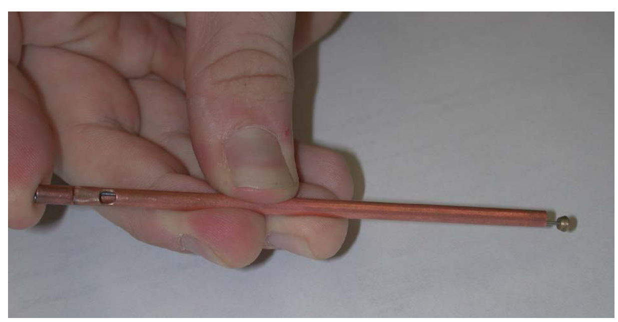

Figure 14. A Sample Tube (minus funnel). The cap is depressed, opening the drain on the far end. Holes near the left end allow powder to enter from the sieve.

2.7. Control Electronics

The MARTE system is controlled through an executive system. This in turn sends serial commands to the CSHS real-time controllers. The CSHS has 18 powered actuators and about twice that many sensors. Most of the actuators need to run under PID position control, some run

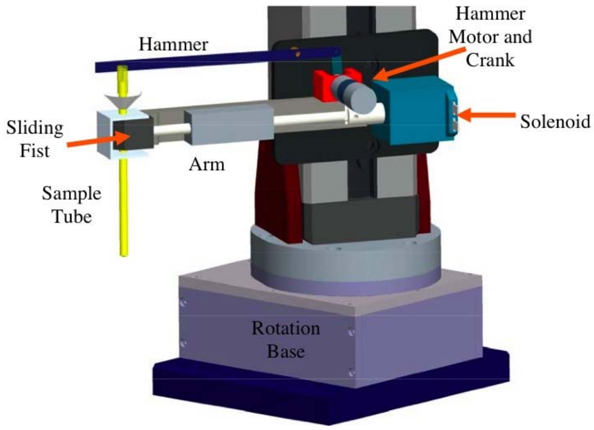

Figure 15. The Transfer Arm mounted on the vertical actuator and its rotational base.

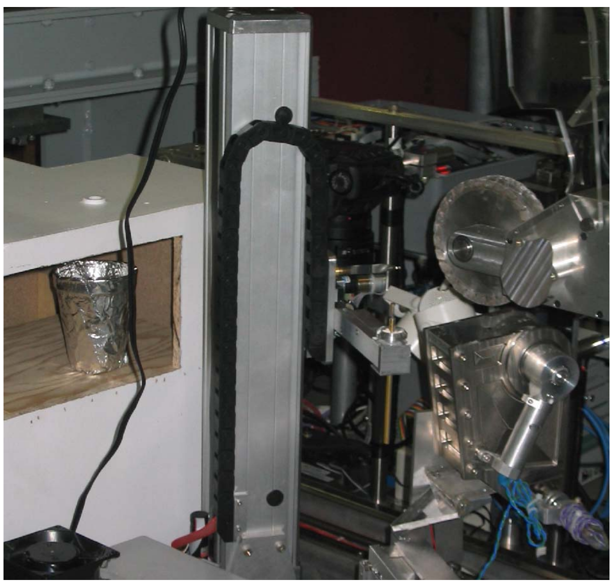

Figure 16. The Sub-sampler is in the position where it dropped the core segment into the crusher. The sample has been crushed and fed into a Sample Tube which is gripped by the Transfer Arm on its way to be inserted into the mockup of the SOLID life detection instrument.

under PID speed control and some operate at set PWM rates. There are a few that do some operations under one control regime and other parts of their operations under a different control scheme. To get the high positional accuracy and repeatability, and maintain the flexibility required, we used a custom controller that was a modification of the XBC robot controller [7, 6]. This controller makes use of a 100K gate FPGA which handles the PID and PWM control along with the digital inputs from the sensors. The FPGA is controlled by an ARM 7 CPU. The CPU and LCD screen for the controller are contained in a COTS *Nintendo GBA*. The FPGA board with its daughter board that contains all of the motor drivers [5], connect through the game port slot on the GBA. This system runs through the control loop at about 200HZ.

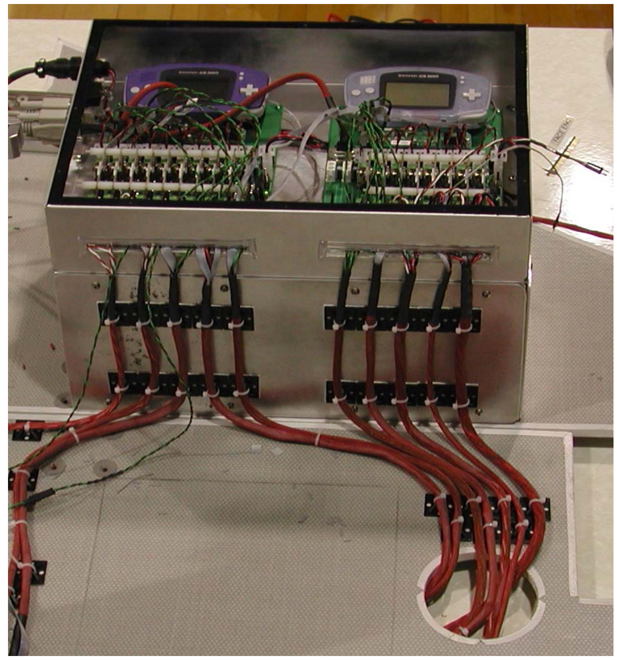

Figure 17. The two control computers and cabling leading to the various components

Each controller can drive up to ten motors each with a high resolution quadrature encoder. Each controller can also read 19 digital ports and 8 analog ports. The controller box contains two of these controllers and is shown in Figure 17.

On high precision mechanical parts such as the Linear Rail or the positioning of the Sub-sampler, the encoder resolution maps to about 1μm per encoder tic. The position control allows cutting speeds as slow as 50μm/second. The positioning accuracies and repeatability are better than 50μm for most of the actuators. This level of control is most needed during sub sampling where an error of 0.25mm can result in sub-sampling the clamp materials in addition to the rock cores. The speed control is used to ensure safe cutting without letting this already time consuming process grow longer. PWM control is used when closing the clamps and docking clamps to the storage system. This provides a near constant torque, but will avoid over tightening the clamps or potential damage should something be misaligned in the storage rail.

3. SYSTEM PERFORMANCE & FUTURE WORK

After several weeks of laboratory testing, in June of 2005 the MARTE system was deployed for its first field test (Figure 18) at a quarry near Santa Cruz, CA in the USA. The goal of this preliminary test was to exercise all aspects of the various MARTE systems and run through at least one full drill cycle. During the week of testing, two very unseasonable rain storms hit the area, dropping several cm of rain at the test site and turning the dirt surface into a quagmire. Testing was temporarily halted and all personnel spent their time covering equipment and digging trenches to keep the bore-hole from flooding.

Despite the environmental challenges, a bore-hole over 1.3 m in depth was drilled and the core was processed by the CSHS. Additionally, several test cores – some sterile and some laced with e-coli, were processed by the CSHS to provide data for cross-contamination studies.

The CSHS system worked very well, though a minor redesign was indicated for the Sample Tube feeder. While only minor rework and optimizations are planned before the more extensive September field test in Rio Tinto, several items did appear that would need to be addressed before an actual flight mission could take place.

Perhaps the most critical is finding some method for measuring the amount of sample powder produced by the crusher. We found that the 40% production rate predicted by [3] is very rock dependent. This could vary either way by more than a factor of 2 depending on the particular chunk being processed. Crushing time also appeared to vary by up to a factor of 4 depending on the orientation at which the rock sample came to rest inside the crusher gullet – some orientations causing the sample to fracture immediately, others taking upwards of an hour before the first powder started to appear.

These changes in crushing speed and output are critical because they preclude an open loop method of filling the Sample Tube. Over filling the tube causes the powder to pack and makes it difficult to release into SOLID. Under filling the tube does not provide sufficient material to SOLID to get a satisfactory analysis.

Another issue that needs to be addressed in future work is dust containment. Dust from cuttings and crushing causes cross contamination as well as potentially degrading equipment and instruments. We currently use a vacuum system to remove the cuttings from the sub-sample saw. We will install a similar system for the Facing Saw. There is some debate whether or not such a vacuum system could be used on Mars. However, tests described in [10] appear to indicate that pressure ratios in air flow rather than the absolute differential are the critical measure for floating cuttings on air. This may mean that vacuum systems for containing dust and cuttings will in fact be practical on Mars.

Experiments in Spain this Fall will be a more thorough test of the CSHS and the rest of the MARTE system. But this preliminary field experiment has validated the CSHS as a highly automated reliable method for cleanly handling rock cores and powder samples.

Figure 18. The MARTE system *lands* at Bonny Doon quarry.

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